XII. SFOF Operations

OPERATIONS AND FACILITIES

A. Man–Machine Interaction in the Post-1971 SFOF, *L. R. Huesmann*

1. Introduction

The basic design for the *Mariner* Mars 1971 SFOF system was derived from JPL's IBM 7094/7044 system and the Manned Spacecraft Center's IBM 360/75 real-time operating system (RTOS). The *Mariner* Mars 1971 mission is the first of a type of mission with some fundamental characteristics quite different from previous unmanned missions and also from the type of mission the Manned Spacecraft Center's RTOS was designed to support. It seems likely that missions in the post-1971 time period will exacerbate the problems created by these fundamental changes to the point that major alterations may need to be made in the SFOF system. The purpose of this research was to outline some of the general problems that the SFOF must face in the post-1971 time period and to suggest how advances in the field of man–machine interaction can be applied to these problems.

2. Characteristics of the Post-1971 Missions

It seems probable that a large number of missions in the post-1971 time period will possess a set of characteristics that has not been typical of earlier missions. First, missions will involve multiple spacecraft active during the same time span, and several missions will be concurrently active. Many spacecraft may require equal attention from the SFOF during a given period. Second, the active period for spacecraft may increase beyond 90 days. Third, the round-trip light time to the spacecraft will usually be long enough to make any sort of real-time control from earth impossible. Fourth, the delay between final testing (launch) and operation of the spacecraft will increase greatly. Fifth, the number of scientific experiments executed during any mission can be expected to increase. Each spacecraft in a multiple-craft mission may carry much more complex scientific equipment than previous flights and engage in a much larger number of experiments. Finally, as a result of these factors, one can expect an exponential increase in the command and control functions that the SFOF system must handle.

Let us now consider some of the major specific problems posed by these changes in mission characteristics.

3. Reliability Problems

The increased complexity, and particularly the increased duration of missions in the post-1971 time period, will

raise serious reliability problems both in the hardware and in the human management of the missions. The probability of a failure simultaneously in both the prime and back-up computing facility at the SFOF cannot yet be estimated but must be kept low for a 3- to 6-month active mission. In addition, the on-board equipment, and particularly the on-board computer, must have a reliability comparable to the earth-based computing facilities. Hence, hardware failure rates low enough for missions in the 1960's will probably be too high for post-1971 missions. In addition, the operator error rates are likely to increase as the missions lengthen. The word "operator" in this context means any human involved in the control of the mission. In particular, the decision makers on the various science and engineering teams can be expected to commit errors on long duration missions requiring constant attention to detail. Jenkins (Ref. 1), Yntema (Ref. 2), and others have found that operator error rates which are quite low for limited periods increase exponentially as the operator is faced with the same task for longer periods and at irregular intervals. A decision maker's performance is likely to be worst on routine tasks requiring concentrated attention at irregular intervals. The important point to remember is that a decision maker's reliability will decrease beyond the extrapolation of daily reliability rates when the above contingencies are encountered.

4. Time and Resource Problems

The second major group of problems to be expected in the post-1971 time period arises from the increased use of fixed resources and the increased activities in any time period.

Presumably, it is desirable on any mission to maintain as short a regular planning cycle as possible during the operation of the mission. Yet, one can expect the regular planning cycles to become very cramped in the post-1971 time period unless they are lengthened beyond the range proposed for the *Mariner* Mars 1971 mission. One can divide a planning cycle into five stages: data acquisition, data analysis, decision making, event scheduling, command generation, and command transmission. It is obvious that with multiple spacecraft, increased scientific experimentation, and more-complex flight plans, the analyses, decision making, scheduling, and command generation times will expand. In addition, since light time will be great enough to prohibit any sort of real-time control, the planning process will be complicated by the need for basing plans on predicted sequences of events and the need for the development of contingency commands that may or may not be executed by the spacecraft. One should also not forget the small but significant strain put on the cycle by the loss of planning time directly due to light time.

The time from acquisition of the last data used in planning to transmission of the last command will be at least one round-trip light time less than the spacecraft activity cycle. For example, for a craft in the vicinity of Jupiter, round-trip light time is about 90 min. Hence, to achieve a 24-h lag between the occurrence of data and the spacecraft's response would require a 22.5-h earth planning cycle. Finally, on post-1971 missions the planning cycle will also be more susceptible to unpredictable overloads. With multiple-craft missions and multiple missions many events will be occurring in parallel. Hence, unusual combinations of unexpected events are much more likely to swamp the system.

Regardless of the planning cycle, at some point the decision makers are faced with the problem of scheduling the events that have been decided upon. As mentioned above, many operations may be executed at the same time. What makes the scheduling particularly difficult is the likelihood of conflicts between events. A number of events may require the same resource or a resource that is only available at specified times, e.g., DSS 14. This is as true of activities within the DSN and SFOF as on-board activities. The events must be scheduled to be completed in as short a time as possible without conflicts. Scheduling tasks in this way is by no means an easy job, and it is one that is beyond the capability of the present *Mariner* Mars 1971 scheduling routines.

5. Real-Time Control Problems

As described above, the impossibility of any real-time control of spacecraft activities increases the complexity of the planning cycle; but this phenomenon also prevents some activities entirely and increases the cost of others. The utility of real-time control is quite mission dependent. On orbiter missions repeated observations can be made at low cost until one is sure the craft obtained the desired information. However, on fly-by and landing missions real-time control can be extremely useful. For example, one would like to be able to employ complex real-time instrument-adjustment algorithms, redirect the scan platform on the basis of received data, and (on lander and exploration missions) avoid obstacles or sample ground material intelligently.

6. Principles for an Advanced SFOF System

Four related approaches for ameliorating the difficulties discussed above have survived scrutiny.

(1) Upgrade the on-board computer.

(2) Incorporate additional redundancy into the human system.

(3) Increase the speed of information transmission and carefully control the dispersal of information to operators.

(4) Automate a much greater portion of the monitoring, analysis, and decision making.

Each of these alterations would contribute to improvement in the three major problem areas expected to develop in the post-1971 time period.

a. Upgrading the on-board computer. Upgrading the on-board computer would have the obvious effect of permitting some real-time control of activities. In addition, and perhaps more importantly, greater reliability of on-board hardware can be achieved with a sophisticated on-board computer. Exactly what sort of increment can be achieved in these areas would depend on how much computing power were provided. However, even a very small on-board computer with an arithmetic central processing unit and priority interrupts could accomplish a great deal.

The ability of such a computer to improve the reliability of the on-board hardware (including itself) is not only within the state of the art, but a prototype of such a computer has been built at JPL. The self-testing and repairing (STAR) computer is capable of diagnosing and correcting both transient and permanent hardware faults in itself (Ref. 3). The only major limitation on extending the computer's diagnosing and repairing functions to other on-board hardware would be the cost of the additional computing power required and the replacement hardware. However, it is known that a specified reliability can be achieved with less hardware redundancy when fault detection, hardware testing, and repair by replacement are instituted. It is appropriate, then, to balance the cost of the additional computing power against the savings in redundant hardware. Fault monitoring could be carried out in real-time by the on-board computer with problems that exceed the on-board computing power relayed to earth. Conceivably, faults fatal to missions without this real-time capability could easily be handled by a small on-board computer. Avizienis (Ref. 3) presents a more comprehensive discussion of the advantages of the replacement method over other means of achieving reliability.

In addition to permitting a repair-oriented approach to reliability, upgrading the on-board computer allows some sophisticated forms of operational control that would otherwise be impossible. Two particular applications will be briefly discussed here: video field control on fly-by missions, and obstacle avoidance during robot exploration of other planets. Many workers in pattern recognition—most recently, Guzman (Ref. 4)—have demonstrated that, in situations where human operators appear to be using very complicated rules to select patterns, a very simple set of rules actually suffices.

The state of the art is such that a reasonably simple algorithm could be developed to direct the scan platform to acquire video targets of exceptional interest in high resolution. One should not underestimate the problems in on-board video processing; but neither should one reject the approach under the false assumption that an appropriate decision algorithm could not be programmed for the on-board computer. To construct the algorithm one would need to study how the human planning teams make the same decisions, extract the principles they use, and construct the algorithm about those principles. Such an approach has been used with success in many problem-solving fields, e.g., Greenblatt (Ref. 5) and Tonge (Ref. 6). Obstacle avoidance and pathfinding by robots has already been studied extensively by artificial intelligence workers, e.g., Nilsson (Ref. 7), Kirk and Lim (Ref. 8). Again, the conclusion to be drawn is that algorithms could be written for an on-board computer so that it could effectively guide an explorer robot. While it is true that the performance of an on-board computer on these two tasks would probably be inferior to its performance if it were controlled by a human operator, one must remember that light time prevents any sort of human control.

Perhaps the major advantage accruing from a sophisticated on-board computer would be the reduction in activities required of the SFOF. Contingency programs and monitoring routines in the on-board computer would reduce the strain on the SFOF.

b. Human redundancy. The major nemesis of human reliability over a long mission is boredom and uncertainty. Errors in routine tasks will become much more probable than a simple extrapolation of daily reliability

rates would indicate. Performance in highly stressful decision-making situations that occur repetitively at irregular intervals is especially affected. The difficulty is that problem solvers must be in a highly attentive, motivationally aroused state to perform at their best. This aroused state simply cannot be maintained over a long period of time for tasks with low probabilities of requiring nonroutine actions at any time (Ref. 9).

The situation can be improved with several modifications to the human information-processing system of the SFOF. First, continuous monitoring of parameters by human operators should not be attempted. The ground-based computing facilities in conjunction with the on-board computer should not only monitor relevant raw data, but should also execute sophisticated analyses of the data in near real-time. The computing system should be capable of determining whether parameters are within acceptable bounds, predicting probabilities that they will continue to be acceptable, and composing commands to adjust parameters, if necessary. Human monitoring should be viewed as a redundant monitoring system to be used if the other system fails. If a critical problem occurs, the system should be able to raise an alarm, display processed data, suggest a remedy, and begin a remedy if time does not permit human intervention. During normal operation, at prescribed intervals during the day, the system would present reports for the operators to study. This technique of involving the human decision maker only at established regular intervals maximizes the reliability of human performance over long periods (Ref. 9).

A second modification would be to introduce operational redundancy into the human decision-making process. Crucial decisions, command construction, and data analyses performed by one man should be verified by at least one other person who operates independently of the first. This is already done informally but should be systematized. The cost of such redundancy is not small and should be reserved for areas where fatal errors are not improbable. For example, a team's input to the command generation program should be verified by an independent decision maker, and a team's confirmation that the command sequence is correct (on the basis of the simulated execution of the commands) should be verified by an independent decision maker.

c. Improving information transmission. The SFOF computing system is a time-sharing system. As with any such system, the response time to a request varies greatly with the load on the system. As a result, one can predict that decision makers frequently will spend significant amounts of time waiting for output that may arrive in 1 s or 10 min. As Nickerson (Ref. 10) has pointed out, even the most sophisticated decision makers find it impossible to operate efficiently under such response uncertainties. Of course, the problem is serious only if users are engaged in several simultaneous tasks and are pressed for time. But this is exactly the situation one expects to occur at the SFOF.

The only solution that has been proposed for this problem is quite difficult for systems managers to accept, since it involves a deliberate delay of information. Yet it undoubtedly increases user efficiency (Ref. 11). The monitor computes a conservative estimate of when the system can respond to the user's request, informs the user of the response time, and responds at that time even if the information is available sooner. Of course, one would want to be able to override this facility in certain emergencies. However, one should note that such a procedure in no way increases the computer's idle time or overhead. Output is simply stored until the appropriate delivery time.

Information transmission between human operators must also be facilitated. The SFOF management system for *Mariner* Mars 1971 divides responsibilities primarily by function. Communication among decision makers is vital for the success of this approach. However, past experience (Ref. 9) provides some evidence that concurrent missions involving many spacecraft will require more division of responsibility by spacecraft for reliable operation. In this situation the ease of communication among operators performing parallel tasks becomes even more crucial. More emphasis will need to be placed on locating hardware and personnel to facilitate communication, selecting operators, and training the human system by simulation.

The SFOF operating system can also ensure improved human reliability and efficiency by carefully regulating the normal distribution of information to the planning teams. One might think that more information is always desirable. Yet it has been found that it is relatively easy to overwhelm decision makers with irrelevant information to the point that they cannot extract the relevant information (Ref. 9). Data distribution to planning teams should be designed to communicate on request exactly what is desired and no more. Though it may seem counter-intuitive, continuous presentation of data is more likely to lead to human error and inefficiency than regular periodic presentations of summary data.

Some strain is also placed on the planning cycle by the SFOF's hardware and software limitations on information transmission speed. For example, the current command transmission rate of 1 bit/s is an order of magnitude too small. Advances in the state of cathode ray tube terminals can be expected to permit more rapid presentation of data to decision makers and the elimination of most mechanical output devices. Advances in the use of engineering psychology in designing terminals should lower error rates as well. Significant advances in the speed of input devices are less likely. However, the input requirements of programs can be designed in ways that minimize the likelihood of user error and minimize transmission times. For example, mnemonics are generally preferable to numeric commands, and an immediate acknowledgment for any input is desirable.

d. Automating human decision making. The fourth conclusion of this report was that greater use needs to be made of the computing facilities in the decision-making process. Actually, many of the above suggested modifications to the SFOF system have involved such a change. It has already been suggested that the on-board computer could make several types of operational real-time decisions and that the SFOF system could assume a large portion of the fault monitoring, parameter adjusting, and repair switching functions human managers have performed in the past. Besides incrementing reliability, this approach would reduce the load on the human planners and improve their performance on other decisions. However, to keep the planning cycle reasonably short, it is proposed that, in addition, the SFOF computing facility must assume a greater burden of the planning functions.

An axiom about decision making to which artificial intelligence researchers have learned to subscribe is that most human decisions are systematic whether the operator knows it or not (Ref. 2). If one can discover the algorithm the decision maker is using, one can program a computer to make the same decision. The computer will usually make the decision more rapidly and consistently than the human operator, although it may suffer defects in its adaptability to new situations (Ref. 2). The typical approach to discovering the algorithm has been to query the decision maker and to study his behavior in controlled situations. This approach has been successfully employed on tasks ranging from scheduling jobs in a factory to playing chess. It is a conclusion of this study that there are excellent chances for the success of such an approach in discovering many of the decision algorithms the planning teams employ. The resulting program would certainly be somewhat inferior to the human planner in handling new situations; so obviously one would employ the human decision makers to verify the decisions. Again, the proposed change is one that makes the human operator a back-up system, reducing the strain on him, and improving his performance on crucial tasks. One specific planning task for which such an approach is virtually a necessity is the previously described problem of scheduling parallel events requiring limited resources. There are no known algorithms for solving this type of problem. Huesmann (Ref. 12) has constructed a program that models human behavior on these problems and does much better than human operators in any reasonable amount of time.

Many will question the ability of the computing facilities to perform the decision-making functions previously executed by men. This skepticism is justified in the light of past experience. However, recently the field of artificial intelligence has advanced to a stage where the implementation of previously experimental techniques is producing large increments in system performance. Several examples have been cited above (Refs. 4, 5, 6, 12). In direct competition with man we have medical diagnoses programs that are more accurate than a single excellent doctor (Ref. 13). Edwards (Ref. 14) has shown that, while sophisticated decision makers are good at forming subjective estimates of the probability of a single event, they are quite bad at combining incoming data and *a priori* probabilities to judge the likelihood of an event. No one is suggesting that all decisions can or should be automated. Rather it is proposed that a selective automation of some decisions would improve the reliability and quality of many decisions.

7. Conclusions

A study was undertaken of the problems the SFOF can be expected to encounter in the post-1971 time period. It was concluded that many of the difficulties could be relieved by four major changes in the man–machine interface. It is proposed: (1) that the on-board computer should be upgraded to assume a portion of the functions previously executed by ground-based machines and decision makers, (2) that crucial human decision-making be executed in parallel, (3) that the ground-based system be designed to disperse information in a way that improves human reliability and efficiency, and (4) that the computing systems assume a greater portion of the decision-making and planning functions. Such alterations should improve the reliability of performance,

reduce the required time for a planning cycle, and permit some desirable activities that cannot be accomplished without real-time control.

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